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Diksha Sharma, Han Dong, Yuan Fang, Aldo Badano, "A compendium of publicly available Monte Carlo transport codes (including new tools) for the simulation of radiation imaging detectors," Proc. SPIE 8668, Medical Imaging 2013: Physics of Medical Imaging, 866858 (19 March 2013); doi: 10.1117/12.2007434

Event: SPIE Medical Imaging, 2013, Lake Buena Vista (Orlando Area), Florida, United States

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A compendium of publicly available Monte Carlo transport codes (including new tools) for the simulation of radiation imaging detectors

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ABSTRACT

Simulations play a vital role in the understanding and analysis of existing and emerging medical imaging technologies. Over the last years, Monte Carlo simulations have become increasingly necessary tools for studying the fundamental limitations and for the design and optimization of medical imaging systems. We compare available open-source software packages from the Division of Imaging and Applied Mathematics at the FDA for modeling scintillator- and semiconductor-based radiation imaging detectors for applications in x-ray and nuclear imaging including MANTIS, hybridMANTIS, cartesianDETECT2, and ARTEMIS. We describe the significant features of these packages and discuss their advantages or disadvantages. We also introduce a graphical user interface which greatly facilitates the set up of simple experiments involving scintillator structures with columnar geometries.

1. MONTE CARLO TRANSPORT CODES

We summarize the main features and compare open-source packages for Monte Carlo modeling of scintillator- and semiconductor-based detectors developed and made available by the Division of Imaging and Applied Mathematics (OSEL/CDRH/FDA).

1.1 MANTIS

MANTIS[1] (Monte Carlo x-rAy, electroN and opTical Imaging Simulation tool) is a package for modeling radiation imaging detectors including x-ray, electron and optical photon transport. MANTIS uses PENELOPE 2006[2] for the x-ray and electron transport and DETECT2 for the optical transport. DETECT2 is a Monte Carlo simulation code for the study of light transport processes in scintillator structures including surface reflection or refraction based on Snell and Fresnel formulae, absorption and scattering, and surface roughness. Although publicly available (`code.google.com/p/mantismc/`), MANTIS is no longer actively supported.

1.2 hybridMANTIS

hybridMANTIS[3,4] is a modified version of MANTIS with significant speed improvements. It uses PENELOPE for x-ray and electron transport and fastDETECT2 for the optical photon transport. hybridMANTIS uses a novel hybrid concept to run x-ray/electron transport in parallel with the optical transport using CPUs and GPUs. A modified penEasy[5] program outputs energy deposition events. This information is used by fastDETECT2 to sample the number of optical photons. Notable new features introduced in hybridMANTIS include on-the-fly geometry and columnar crosstalk (CCT).

On-the-fly geometry allows for columns to be modeled dynamically instead of stored in memory (as done in MANTIS) for large-area detectors. Because every column is modeled on the fly, columns can have randomness (including shape, size, tilt angle). CCT allows photons to cross over to adjacent columns without undergoing reflection or refraction at the column boundaries. The current version of hybridMANTIS defines a linear CCT profile with depth.

Due to the use of hybrid concept, on-the-fly geometry and multi-architecture utilization, hybridMANTIS is typically 600 times faster than MANTIS (`code.google.com/p/hybridmantis/`).

Medical Imaging 2013: Physics of Medical Imaging, edited by Robert M. Nishikawa, Bruce R. Whiting, Christoph Hoeschen, Proc. of SPIE Vol. 8668, 866858 · © 2013 SPIE · CCC code: 1605-7422/13/$18 · doi: 10.1117/12.2007434

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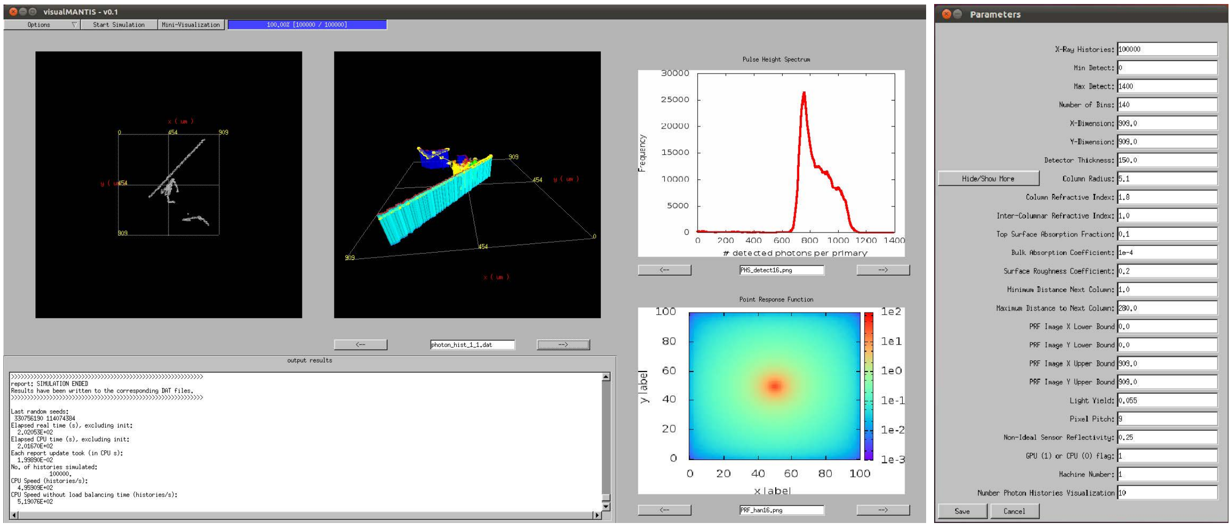
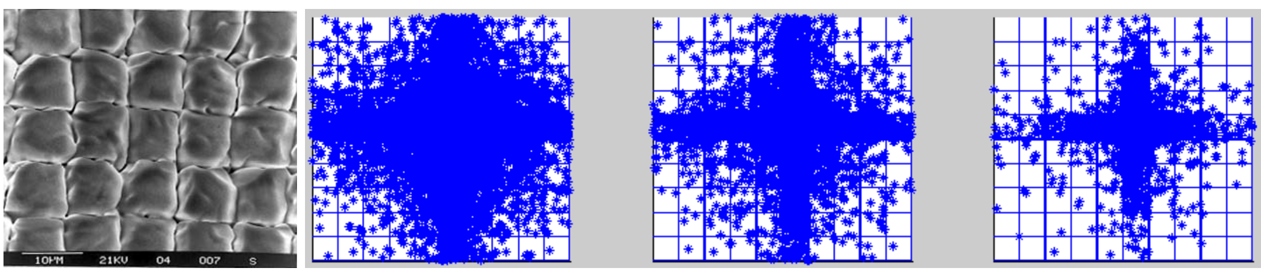


(a) Main screen (b) Input

Figure 1. Graphical user interface (GUI) for hybridMANTIS. (a) Main screen showing the pulse height spectrum, optical photon track overlay on top of actual columnar geometry, and point response function (left to right). At the bottom, output display including the optical transport statistics (number of photons generated, detected, absorbed, etc.) and simulation speed. (b) Input window for the optical transport parameters.



(a) (b)

Figure 2. (a) Top-view SEM of a thick CsI:Tl film (courtesy of RMD Inc). (b) Point responses for a pixelated scintillator.

1.3 visualMANTIS

We have developed a graphical user interface (GUI) for hybridMANTIS to facilitate the set up of computational experiments and to provide real-time visualizations (`code.google.com/p/hybridmantis/`). The tool is built using OpenGL[6] and Fast Light Toolkit (FLTK).[7] OpenGL provides interactive visualization while FLTK helps configuring the GUI. The code output consists of the point response function (PRF) image (detected photons at the sensor plane) and pulse height spectra (PHS), updated while a simulation takes place in the GPU. The tool allows the user to view several optical photon tracks through the detector columns, enabling the user to visualize a particular number of histories (which the user inputs in the Options window), starting from the first history. The user can also visualize how the columns are getting built and photons transported (see Fig. 1).

1.4 cartesianDETECT2

cartesianDETECT2 (`code.google.com/p/cartesian-detect2/`) is a dedicated Monte Carlo optical transport tool available especially for pixelated detector structures used in PET and SPECT imaging[8,9] (see Fig. 2). Some unique features include the physics of DETECT2 and columns identified by their x and y position indices not stored in memory.

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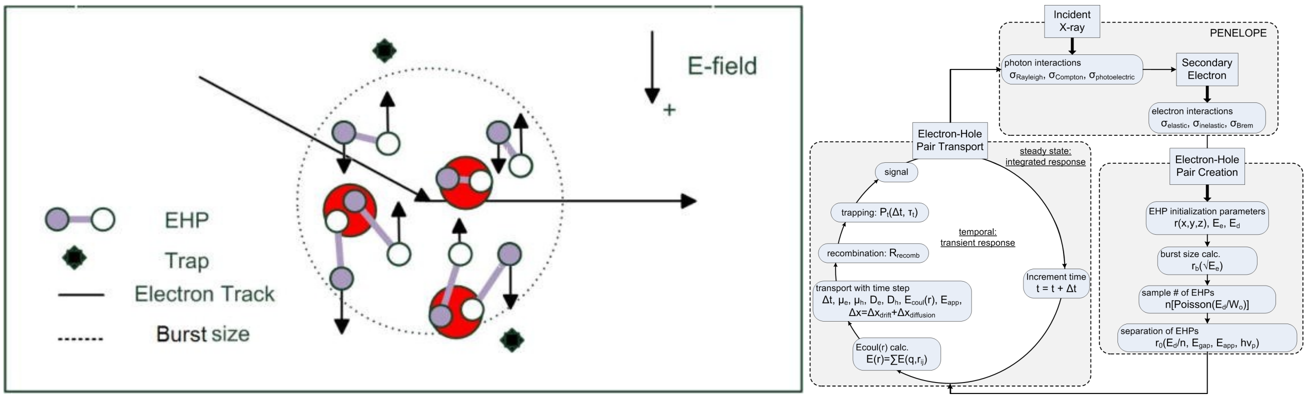

(a) (b)

Figure 3. (a) Two-dimensional illustration of processes related to the creation and transport of electron-hole pairs. Recombination is represented with circles containing an electron and a hole.[11] (b) Flow chart for the simulation of signal formation process in semiconductor x-ray detectors. For details, see Ref. 11.

1.5 ARTEMIS[10]

ARTEMIS[11] (pArticle transport, Recombination, and Trapping in sEMiconductor Imaging Simulations) is a Monte Carlo package for x-ray, electron, and electron-hole pair (ehp) transport. X-ray and secondary electron interactions in the presence of an electric field are modeled by PENELOPE, and the locations of inelastic electron interactions are coupled in space and time to the transport routine for ehp simulation (`code.google.com/p/artemis/`, see Fig. 3).

Major elements of the simulation code include:

- Number of ehp calculated from Poisson distribution as a function of energy deposition and ionization energy.
- Energy deposited divided equally among the created ehp, and thermalization separation distance calculated.
- The burst radius is a function of the electron velocity, and in conjunction with the thermalization distance, generates a distribution of ehp.
- The applied bias and coulomb field between carriers are taken into account along with electron and hole mobilities, and carrier drift and diffusion.

2. DISCUSSION

Table 1 presents a comparison of the main features of indirect detector modeling codes. The codes presented in this paper have different degrees of validation work associated with them. Most notably, MANTIS has been validated against experimental measurements for four different CsI screens with a variety of thicknesses and substrates.[12] In addition, hybridMANTIS has been compared to previously published experimental and MANTIS data on detector response functions[13] and has been found to match the experimental results better than MANTIS for most screen designs. Finally, ARTEMIS preliminary Swank factor results have been compared to experimental measurements from Blevis *et al.*[14] Simulated and experimental Swank factors are within approximately 2%.

Although these tools are already publicly available, a comparative review of the codes is currently not available in the literature. The comparison presented in this paper might help users select the right package for their application and understand their advantages and disadvantages. We also introduce the new visualization tool for hybridMANTIS which will greatly facilitate the setup of simple computational experiments.

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Table 1. Comparative table with timings and main features of the Monte Carlo simulation codes described in this paper for the modeling of indirect x-ray imaging detectors.

	mantis	hybridmantis	cartesiandetect2
General features			
GPU-accelerated	No	Yes	No
GUI	No	Yes	In preparation
Free download	`code.google.com /p/mantismc/`	`code.google.com /p/hybridmantis/`	`code.google.com/p/ cartesian-detect2/`
Optical transport			
Code	detect2	fastdetect2	cartesiandetect2
On-the-fly geometry	No	Yes	Yes
Columnar crosstalk	No	Yes	No
Rayleigh scattering	Yes	No	No
Wavelength effects	Yes	No	No
Polarization	Yes	No	No
Optical sensor	Non-ideal	Non-ideal	Ideal
Language	Fortran	C, CUDA[a]	C
Timings			
Code	mantis	hybridmantis	cartesiandetect2
Total time[b]	277:46:12[c]	00:26:43[d]	55:00:55[c]
Speed (x-ray hist/sec)	1	627	5[e]

[a] A parallel programming model developed by NVIDIA® Corporation.
[b] Timings for 10^6 histories for a 909×909×150 μm^3 detector.[3]
[c] Using 1 core of Intel® Xeon® E5410 CPU.
[d] Using 1 core of Intel® Core i7 920 CPU and an NVIDIA® GeForce GTX 580 GPU.
[e] Estimated based on equivalent runs for diagnostic x rays (only optical).

3. CONCLUSION

We describe and compare various publicly available Monte Carlo transport codes from the Division of Imaging and Applied Mathematics at the FDA for modeling radiation imaging detectors and list features available for each of them. This comparison can help users get an overview of these codes and choose the right software package for their research problem. We also introduce a visualization and graphical user interface for the hybridMANTIS package that can aid the setting up of computational experiments. These software packages are essential tools for the understanding the underlying physical processes in imaging systems and for the development of future medical imaging products.

4. ACKNOWLEDGEMENTS

YF acknowledges support from Carl A. Pollock postgraduate fellowship award. HD and YF acknowledge funding by appointments to the Research Participation Program at the CDRH administered by the Oak Ridge Institute for Science and Education through an interagency agreement between the U.S. DOE and the U.S. FDA. This work (YF) was also supported in part by the Natural Sciences and Engineering Research Council of Canada. The mention of commercial products herein is not to be construed as either an actual or implied endorsement of such products by the Department of Health and Human Services. This is a contribution of the FDA and is not subject to copyright.

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